Date: December 31, 2015

EIC Detector R&D Progress Report

Project ID: eRD_6_
Project Name: Proposal for tracking and PID detector R&D towards an EIC detector
Period Reported: from July 2015 to December 2015
Project Leader:
Brookhaven National Lab: Craig Woody
Florida Tech: Marcus Hohlmann
Stony Brook University: Klaus Dehmelt, Thomas Hemmick
University of Virginia: Kondo Gnanvo, Nilanga Liyanage
Yale University: Richard Majka

Contact Person: Klaus Dehmelt

Project members
Brookhaven National Lab: B. Azmoun, M. L. Purschke, C. Woody
Brookhaven National Lab - Medium energy group: A. Kiselev
Florida Tech: M. Hohlmann, A. Zhang
Stony Brook University: K. Dehmelt, A. Deshpande, N. Feege, T. K. Hemmick
University of Virginia: K. Gnanvo, N. Liyanage
Yale University: R. Majka, N. Smirnov

Overview

The EIC facility and physics program will require developments in many areas at or beyond the present state-of-the-art in detector technology. Key among these will be the tracking systems and particle ID. Tracking technology spans a rather large phase space of technology, each branch of which has various advantages (position resolution, small radiation length, etc...). The physics program requirements will drive the community both to the best existing technology choices as well as to the key areas wherein the state of the art must be advanced. Often tracking technology serves intrinsic particle identification functions or is most naturally paired with particular PID technologies. For this reason tracking and PID technologies are often closely linked and should be considered as a package rather than separately
The eRD6 Collaboration dates to the first round of EIC R&D funding and is among the first of the so-called “Consortia” combining efforts and resources for tracking and PID technologies across multiple institutions with similar interests and talents. The principle goal of that program was to work toward a sector test of forward tracking prototypes

and PID during a single beam period. This sector test has already taken place in October 2013. Groups from Brookhaven National Lab, Yale University, University of Virginia, Florida Institute of Technology, and Stony Brook University set up apparatus using four of the six available stations at the Fermilab Test Beam Facility. This effort is the largest to date at FTBF and was comprised of 19 detectors stations all of which worked flawlessly and collected data over a three week period. BNL tested a minidrift detector to demonstrate that this device can overcome the resolution degradation experienced by most MPGD detectors for tracks impinging at large angles. Yale tested the so-called 3-coordinate readout scheme which allows for reduced channel count from tracking chambers by adding geometrical pattern recognition to the standard charge-matching technique. UVA and Florida Tech tested multiple detectors including prototypes at “full-size” EIC as well as channel-count reduction via the zig-zag charge division. Stony Brook tested their compact RICH (1 meter radiator CF_4 as compared to 3 meters used by LHCb) to demonstrate clean hadron ID up to 32 GeV/c (highest available secondary beam energy at FTBF).
The ongoing R&D is concentrating on improving the detector performances based on experience obtained and introducing procedures for getting a better handling of the detectors under consideration. New ideas are being investigated and play an important role in the future development of detector R&D.

Past

What was planned for this period?

Brookhaven National Lab:

We planned to finish the analysis of all data from the minidrift detector, write up the results and submit them for publication.
We planned to study the TPC portion of our prototype TPC/Cherenkov detector using cosmic rays, radioactive sources and X-Ray sources. This was mainly to study the field cage in various configurations, including determining HV breakdown thresholds, and to study different gases in terms of their drift velocity and ability to operate with the GEM detectors. We also hoped to start to study the Cherenkov part of the detector and study its interplay with the TPC part of the detector. Also, while it was not initially planned, we also started to investigate new readout patterns for the chevron readout board for the TPC. These have so far been mainly calculations, but we hope to continue these studies with actual detector tests.

Florida Tech:

Submit a paper to NIM on the results of the beam test of a large-area GEM with zigzag readout strips, followed by a second paper on examining the geometric mean method for resolution studies.

Set up the large zigzag GEM detector in our lab and measure its gain and uniformity with an X-ray gun since the gain was actually not measured in the beam test.

Design frames, drift board, and readout board with improved zigzag strips for a complete design of the next chamber prototype for the EIC forward tracker.

Study the performance of small GEM detectors with zigzag strip readout in a magnetic field using our small table-top 1T magnet.

Stony Brook University:

We were planning to optimize the pad structures for charge dispersion.
Furthermore it was planned to work on refurbishing an in-house evaporator and upgrading it to a high-vacuum device with appropriate instrumentation. This device is foreseen to allow evaporating large mirror structures with protective and di-electric coating. We are aiming on structures with sizes of about 1 m x 0.5 m area.

University of Virginia:

- Submit the paper on the FTBF test beam results for publication in NIM A or TNS peer-review journal
- Continue the collaboration on the common GEM foil design with Florida Tech, Temple University and Tech Etch Company.
- Complete the design of the support frames and u/v readout board for EIC-FT-GEM prototype II
- Investigate the feasibility of large Cr-GEM foil with Tech-Etch and CERN.

Yale University:

3-Coordinate GEM
During the past period it was planned to complete the analysis and prepare a paper on the results.

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas (2-GEM+MMG)
During this period it was planned to make measurements on the 2-GEM+MMG gain structure using resistive coatings or planes to reduce discharge probability and possibly spread the signal spatially on the readout plane.
It was also planned to acquire wire planes and begin studies of the extended gated grid structure proposed by Howard Weiman.[i]
A paper on the results on the 2-GEM+MMG studies with different gases was to be prepared.

What was achieved?

Brookhaven National Lab:

The analysis of all the data from the minidrift detector is now complete. The results have been written up and have been submitted for publication in the IEEE Transactions on Nuclear Science. The paper was submitted in late August 2015 and is now under review. We have received the first round of comments from the referees and will submit our response by the end of this year. We therefore hope to have the paper published in early 2016.

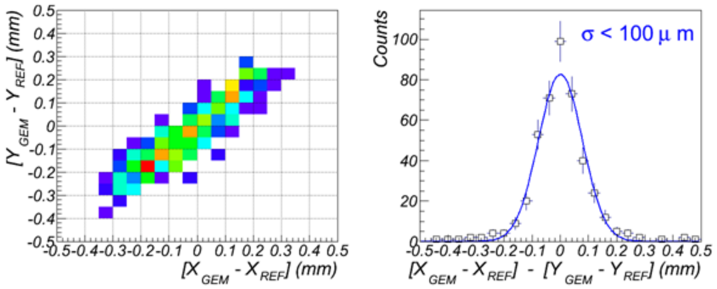

Figure 1 Left: Correlation between the GEM residuals and the reference silicon telescope in the X and Y projections. Right: Projected resolution along the diagonal in Figure 1 left where the correlations between the X and Y coordinate measurements cancel out.

One additional analysis that was added just before submitting the paper for publication was a study on the “ultimate” resolution one can achieve with the minidrift detector. Our tests were hampered by limitations in the SRS readout system, which was not really designed for any type of drift detector, but we nevertheless managed to extract excellent position resolution from the data. We showed that by deconvoluting the pulse shape from the time sliced data, it was possible to achieve a resolution well below 100 μm even at large angles. An example of these results taken from the paper is shown in Figure 1.

TPC/Cherenkov

The construction of the main part of the TPC-Cherenkov prototype detector has now been completed and we have been studying the TPC part of the detector in the lab using cosmic rays, radioactive sources and X-ray sources. We have studied the detector using a variety of different gases, some of which would be useful only for operation as a TPC, while others would be suitable for TPC/Cherenkov operation. The requirement for TPC/Cherenkov operation is that the gas be transparent into the deep VUV in order to achieve good photon detection efficiency, and that it also serve as the operating gas for both the TPC and Cherenkov GEM detectors. This leads to mixtures involving CF_4 and Ar, both of which are transparent into the deep UV, as shown in Figure 2, and are also gases that have been used to operate GEMs.

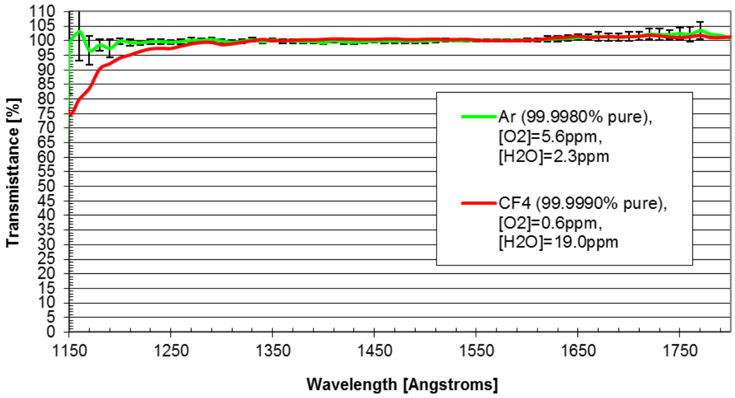

Figure 2 Transparency of Ar and CF_4 in the deep UV.

Figure 3 gives a compilation of a number of gases that could be used with the detector. Mixtures of CF_4 and Ar can provide a fast drift velocity at a relatively low electric field, and would provide good transparency for TPC/Cherenkov operation. We have so far studied Ar/CO_2 (70/30), Ar/CO_2/CF_4 (80/10/10), Ar/CH_4 (80/20), Ar/CF_4 (95/5) and pure CF_4, and we plan to investigate several others gases in the coming months.

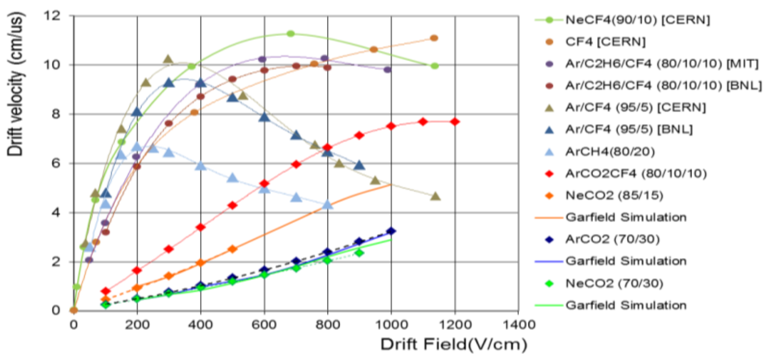

Figure 3 Compilation of drift velocities versus drift field for various gases that could be used for operating the TPC or combined TPC/Cherenkov detector.

We also studied the operation of the TPC part of the detector in both the TPC only and the TPC/Cherenkov configuration. Figure 4 shows the field cage which consists of a double sided kapton foil with 4 mm copper strips. One part is a three sided foil that remains a fixed part of the detector and the second part is a fourth side that is removable. In the TPC only mode of operation, the fourth side is another kapton foil similar to the

other three sides. For operation as a TPC/Cherenkov, the fourth side is replaced by a wire plane, shown on the right in Figure 4, which consists of 75 μm wires spaced 1 mm apart that are connected in groups of four and held at the same potential in order to achieve the same field gradient as the copper strips on the kapton foil.

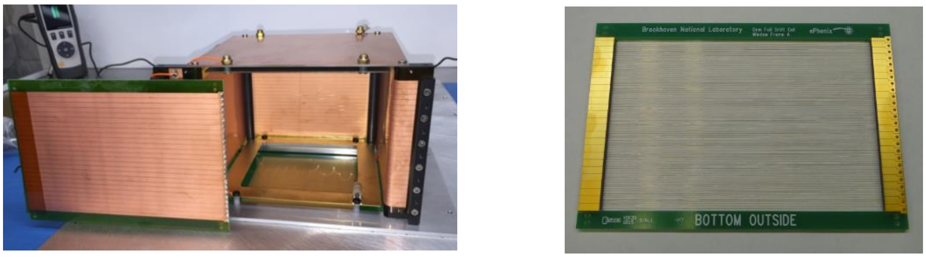

Figure 4 Left: Kapton foil field cage showing three sided foil with fourth side removed. Right: Fourth side wire plane that is used for Cherenkov operation.

Figure 5 shows cosmic ray tracks found in the detector operating in Ar/CH_4 (80/20) using both the four sided kapton foil field cage and with one sided wire plane. Well reconstructed cosmic ray tracks were found in both configurations. The length of the reconstructed track was limited by the number of time samples that could be collected with the SRS readout system, and by the relatively slow drift velocity of the gas that was used. The distortions at the ends of the reconstructed tracks, which occur in both configurations, we believe are caused by effects in the track reconstruction algorithm and are not due to distortions of the field caused by the wire plane. Figure 6 shows the correlation in the angle of the cosmic ray tracks measured with the TPC and the angle

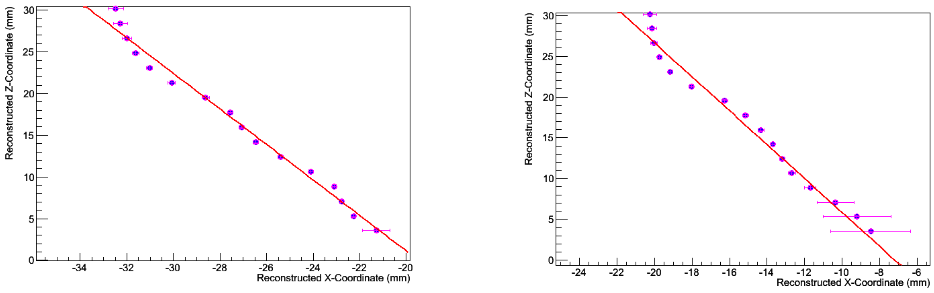

Figure 5 Cosmic ray tracks found in the TPC portion of the detector operating in Ar/CH_4 (80/20). Left: Four sided kapton foil field cage, Right: Field cage consisting of three sided kapton foil and one side of wires.

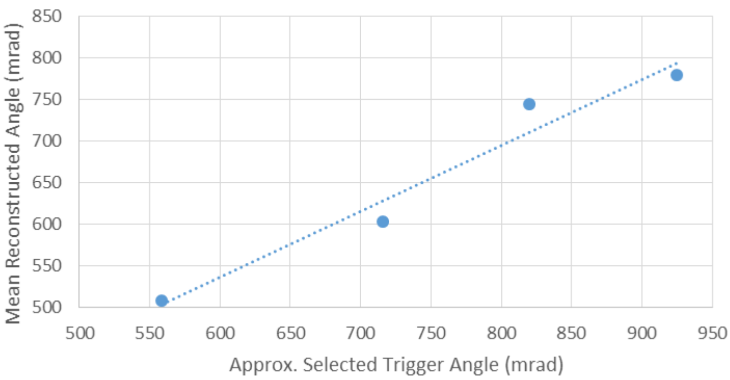

Figure 6 Correlation between the angles of cosmic tracks measured in the TPC versus the angle of the track determined by the cosmic ray trigger counters.

measured by the cosmic ray trigger counters, which shows that the angle measured with the detector is well correlated with the true angle.
We also measured cosmic ray tracks using pure CF_4. This is an ideal gas for Cherenkov operation and was used very successfully in the PHENIX HBD. Figure 7 shows the distribution of cosmic ray tracks measured with the TPC operating in pure CF_4 over a range of angles selected by the trigger counters. Again, a good correlation of the tracks

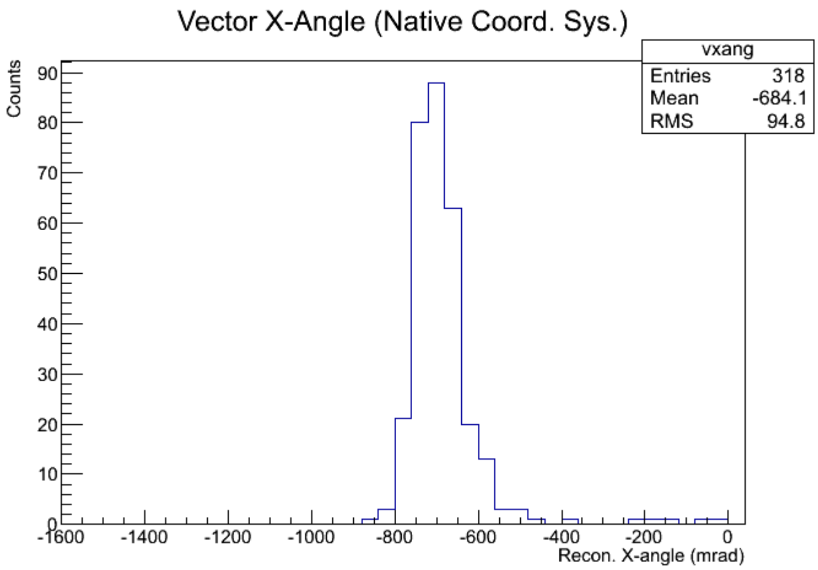

Figure 7 Distribution of angles of cosmic ray tracks measured in the TPC operating with pure CF_4 and the detector configured with the wire plane for TPC/Cherenkov operation.

measured in the detector was observed.

Florida Tech:

Publishing R&D results

We submitted an article on the 2013 beam test at the Fermilab Test Beam Facility (FTBF) to NIM A. The paper was recently accepted for publication. As of the time of writing this report, the article is in press.
We reported the overall status of R&D on forward tracking (FT) detectors for the EIC at the 2015 IEEE NSS/MIC conference in San Diego and submitted a conference record. This talk and paper covered the combined R&D of the eRD3/eRD6 FT groups (Fl. Tech, Temple U., U. Virginia).

Gain and uniformity measurements for the 1-m long GEM detector

We measured the gas gain and response uniformity for the 1-m long GEM detector that was tested at Fermilab in 2013 in our lab at Florida Tech. The X-ray gun (AMPTEK Mini-X X-ray generator) was pointed at 30 "holes" (3 rows, 10 columns) on the back of the drift board where the PCB had been machined down previously to reduce the material (Figure 8).

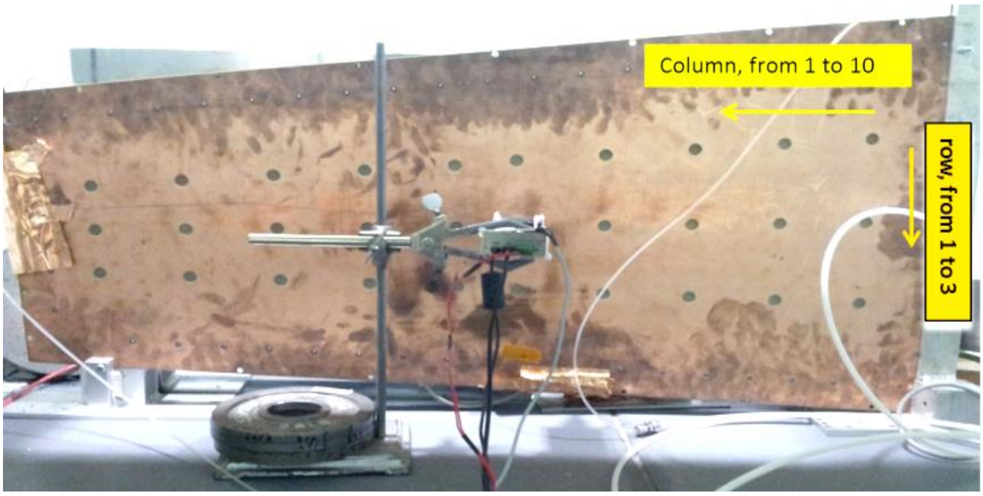

Figure 8 Setup for measuring gain and uniformity of the 1-m long GEM detector with X-rays.

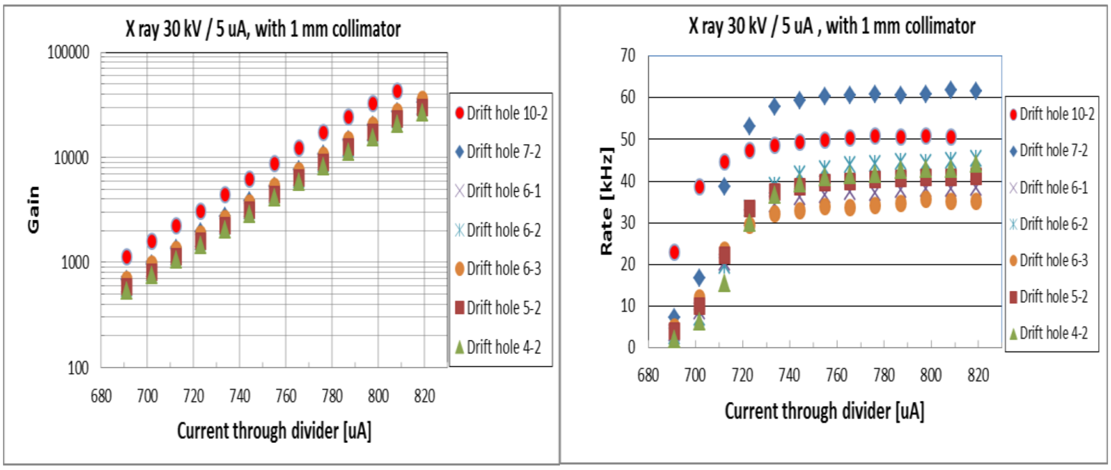

Figure 9 Measured gas gain and counting rate at selected positions vs. current through the HV divider that supplies the GEM potentials for the 1-m long GEM detector.

Figure 9 shows the gain and counting rate measured for the 1-m long GEM detector using signals picked up from the bottom of GEM3. The X-ray gun was set at 30 kV and

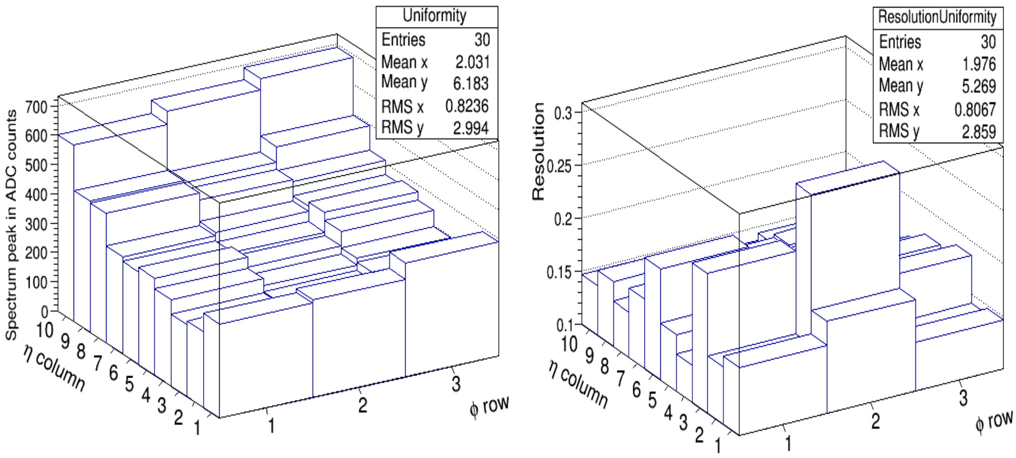

Figure 10 Response uniformity (left) and relative energy resolution uniformity (right) for the 1-m long GEM detector based on the measured pulse height spectrum.

5 μA. We obtain fairly consistent gain curves and rate plateaus, and the gain reaches 3×10^4 in Ar/CO_2 70:30. Figure 10 shows the response uniformity and energy resolution uniformity measured from the position and width of the 8 keV copper fluorescence peak in the pulse height spectra. We observe the highest response at holes in column 10 at the small end of the detector and near the gas inlet. This could be due to either a small gas leak in the detector that causes some O_2 contamination near the outlet region which

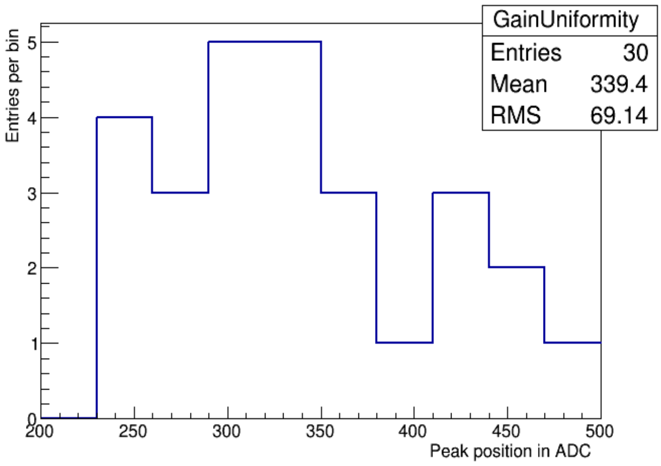

Figure 11 Measured overall response uniformity for the 1-m long GEM detector using 30 irradiation spots (rms/mean = 69.1/339.4 = 20.4%).

reduces the gain there, or due to a known slight deformation of the PCBs so that column 10 has smaller gas gaps. Overall, the response uniformity is measured to be 20% (rms) (Figure 11).

Design of frames, drift, and readout for the next FT GEM prototype chamber

We described the common EIC GEM foil design in our last report. Kondo Gnanvo (U.Va.) worked with the CERN workshop to add the actual GEM holes to our design. That completes the common GEM foil design.

To assemble a GEM chamber from the common GEM foils, Florida Tech intends to use the mechanical stretching technique that was pioneered by the CMS GEM collaboration for the CMS muon endcap upgrade. The original mechanical stretching technique uses a stack of 3 GEM foils and puts the drift electrode and readout structures on solid printed circuit boards (PCBs). However, this results in significant amount of material within the active detector area, which is not optimal for EIC tracking purposes. The potential problems are multiple Coulomb scattering of charged particles and a non-negligible probability for electron showering in the material, which causes systematic effects in the measurement of scattered electron momenta that can be hard to track.

Consequently, we modify the original mechanical stretching technique by designing a stack of 5 foils (3 GEM foils, 1 drift foil, and 1 readout foil) that is sandwiched between two outer frames made of stiff material and stretched against posts that are also sandwiched between the outer frames. Both frames will have thin windows, e.g. made from 100 μm aluminized mylar foil, so that the material in the active detector area is minimized. High-strength but low-mass material such as carbon fiber will be investigated for the frames since PCB frames may not be strong enough to hold their shapes under the stress required to stretch the foils. An outer frame surrounding all posts will seal the gas volume.

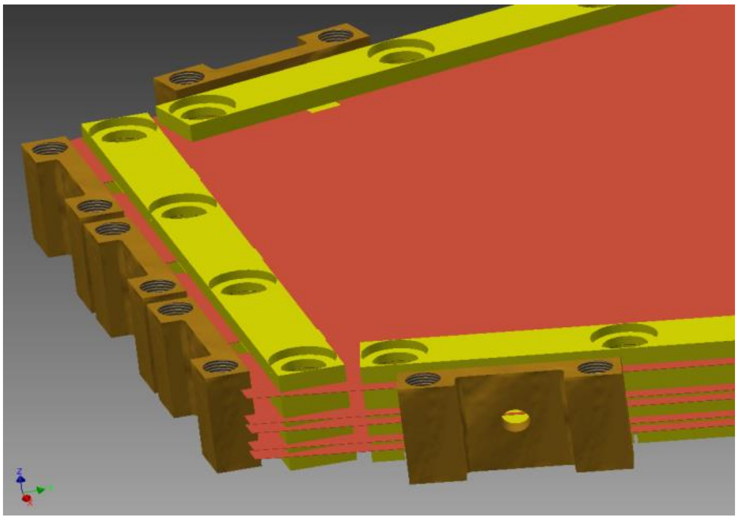

Figure 12 CAD drawing showing the Triple-GEM detector design to be assembled with the modified mechanical stretching technique. Five foils (red) are sandwiched between small inner frame pieces (olive green) that get stretched against posts (brown). The posts themselves are to be sandwiched between large stiff outer frames (not shown) to provide mechanical stability.

We have produced a complete CAD drawing (Figure 12) for this modified stretching technique. Designs of frames and posts have been completed in AutoDesk Inventor. The drift foil design, which contains just a solid copper surface and an HV pad, and the readout foil design, which is quite complex, have both been completed in Altium.
For the readout, we again use zigzag strips to minimize the number of required

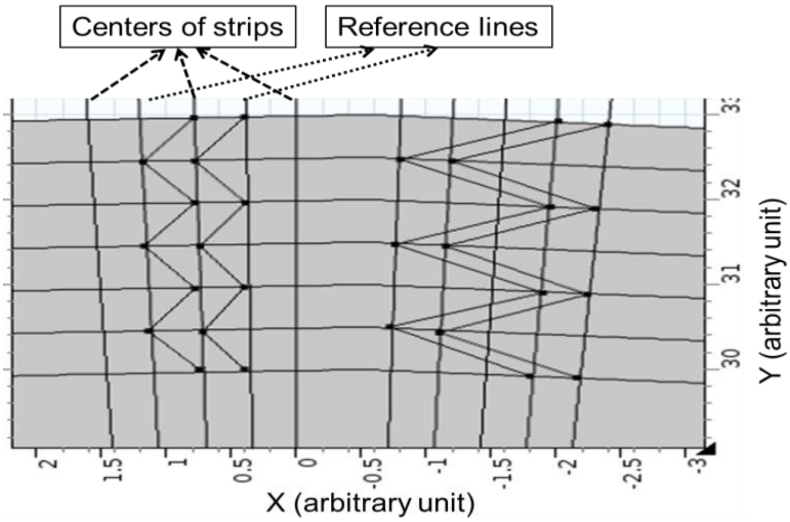

Figure 13 Two types of zigzag strips running radially; the zigzag strip on the left shows that tips on one strip do not exceed two reference lines, while on the right the tips of a zigzag strip reach the centers of its neighboring strips.

electronic channels while preserving good spatial resolution. In our previous zigzag design (Figure 13, left), the locations of the tips on a zigzag strip were constrained by only two reference lines with limited interleaving of zigs and zags giving rise to a central "spine" on each strip in the actual physical implementation on the PCB. This resulted in a nonlinear response when constructing hit positions from the charge centroid method. Inspired by Alexander Kiselev's efforts to optimize the zigzag strip structure (see below), the new design for the second FT GEM prototype will feature zigzag strips with tips that will reach the center lines of their neighboring strips (Figure

13, right). This should optimize the charge sharing and give a more linear response across the entire strip.

Figure 14 shows an overview of the full readout design for the EIC-FT-GEM-Prototype-2. We divide the readout area into five radial regions. In sector 1 at smallest radius, which extends 12 cm in radius, we use 128 straight strips in order to achieve best spatial resolution and lowest occupancy since the sector width here is quite small (~4 cm); here the angular pitch of the strips is 4.14 mrad. Sector 2 also has a radial length of 12 cm, but is read out with 128 zigzag strips (also 4.14 mrad angular pitch). Sectors 3-5 have a radial length of ~22 cm each and 384 zigzag strips, so the angular pitch in the three sectors is 1.37 mrad. Nine APV hybrids (1152 channels) placed at the wide end of the trapezoid suffice to read out the entire detector.

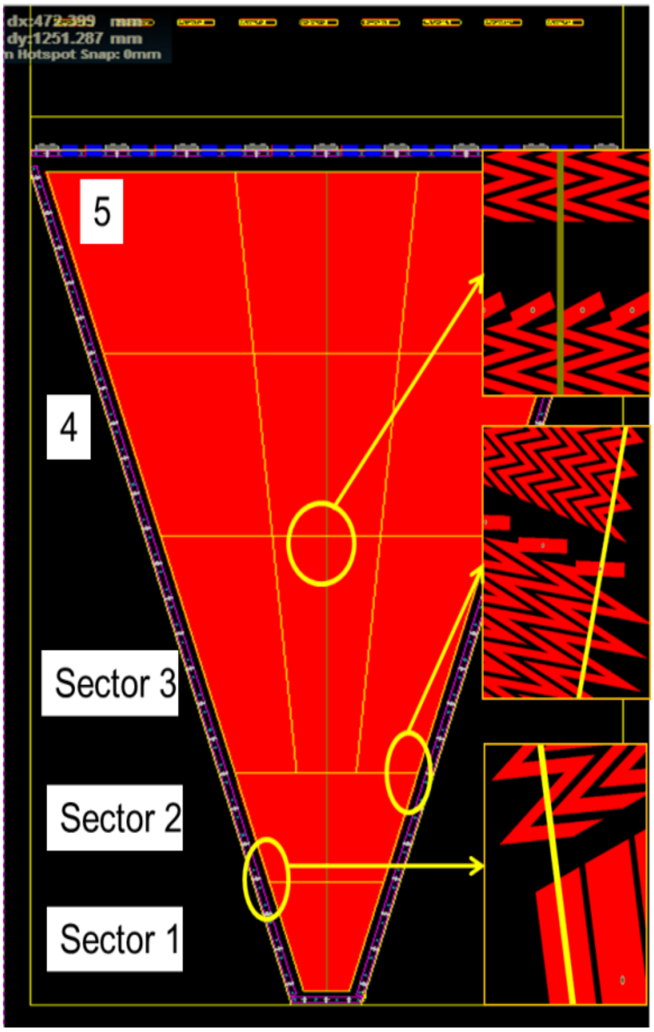

Figure 14 The readout design for the EIC-FT-GEM-Prototype-2 with five different sectors. Sector 1 has straight strips and the other sectors feature zigzag strips. All strips run radially. Design details are shown in zoomed-in views of three different sector transition regions on the right.

Another objective of this new design is to place all readout electronics at the wide end of the detector. Routing of traces from the readout strips to Panasonic connectors that the APV hybrids can plug in at the wide end proved to be quite complicated due to the special strip arrangement. Based on a 2-layer PCB design sketch, vias (or via-like holes) must be used. Figure 15 shows the finalized routing scheme. In this design, 50 µm diameter vias are used. There are 128 vias each for Panasonic connectors 2-8, and 64

vias each for Panasonic connectors 1 and 9; so the total number of vias near the Panasonic connectors is $128 \times 7 + 64 \times 2 = 1024$. There are an additional 640 vias

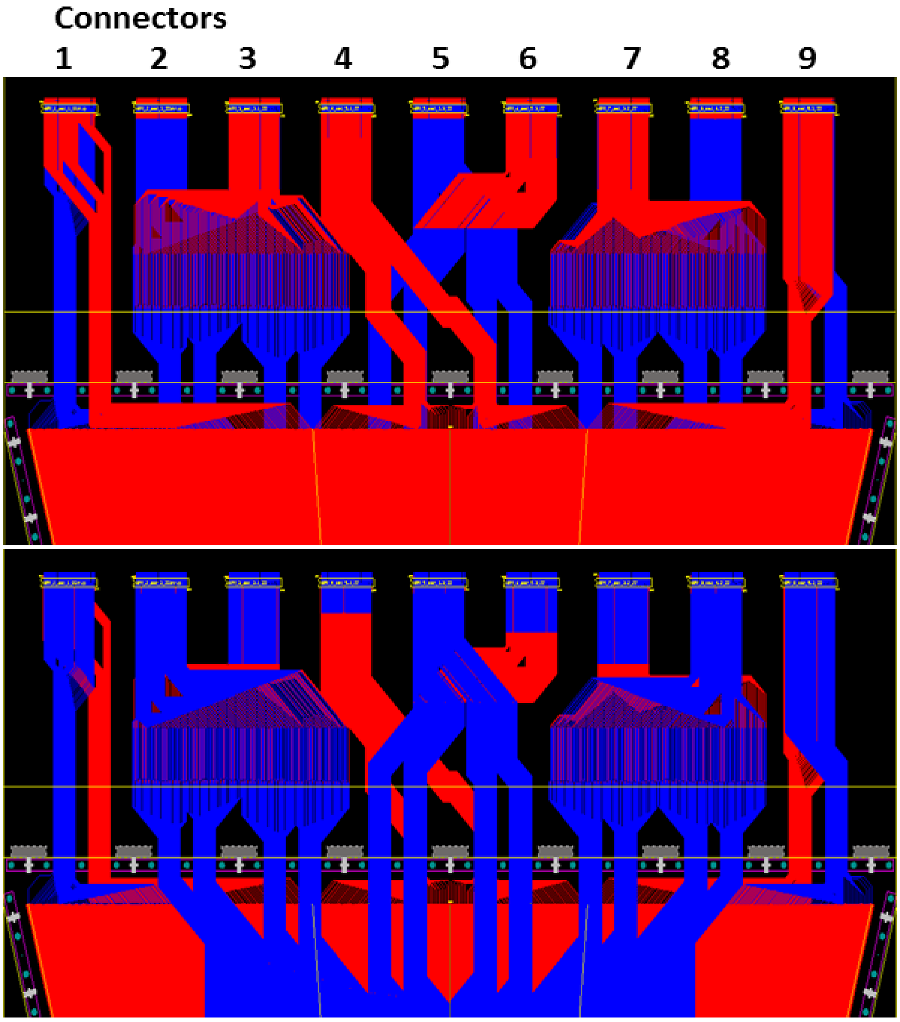

Figure 15 Routing of traces from readout strips to Panasonic connectors at the wide end of the trapezoid foil, based on a 2-layer PCB design in Altium. The traces in red are on the top surface (same as the readout strips), while traces in blue are on the bottom surface. The top (bottom) plot shows views from the top (bottom) surface.

in the region outside the frames, and 896 vias on the readout strips. The total number of vias required is 1024+640+896=2560.

High-resolution scans of zigzag readout board responses

In order to better understand the performance of zigzag strips, we scanned zigzag strip readout boards installed in a 10cm × 10cm Triple-GEM detector with an X-ray gun mounted on a 2-D movable stage at BNL (Figure 16). The X-ray output energy is 5.9 keV and the beam is collimated by a slit of 0.05 mm by 8 mm giving a typical rate of a few Hz. The X-ray gun is mounted on a 2-D motorized stage which can be moved with a very small step size (~1 μm) in both X and Y directions.

We scanned two zigzag boards; one board has 30 strips and the other one has 48 strips. The zigzag strips on the two boards run radially and are equivalent to the geometry of the zigzag readout of our first 1m-prototype detector at different R coordinates

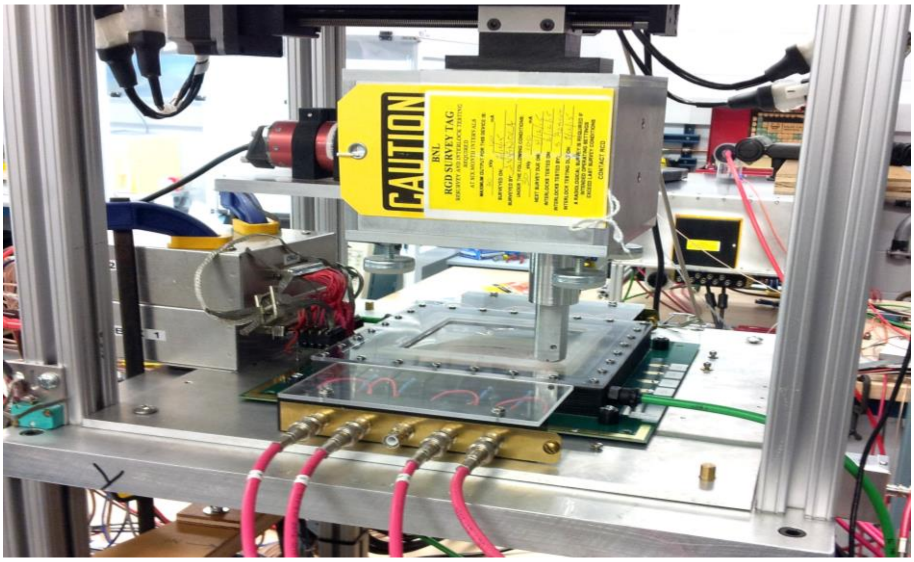

Figure 16 Setup for scanning a 10 cm × 10 cm GEM detector with an X-ray gun at BNL. The motorized stage can be moved in both X and Y directions with a minimal step size of about 1 micron.

corresponding to the narrow and wide ends of the trapezoid (R=1420-1520 mm for the 48-strip board, R=2240-2340 mm for the 30-strip board). The angular pitch of the zigzag strips is 1.37 mrad for both boards. These boards were designed following the idea shown in Figure 13 (left). Figure 17 (left) shows the zigzag strip design for the 48-strip board. After the boards were produced by a PCB factory (American Circuit Inc.), we noticed that the "spine" on the center of each strip were considerably thicker (Figure 17, right) because the tips and valleys are not as sharp in reality as in the design. The same applies to the zigzag readout board of the first 1-m prototype detector.

In the summer, the two Florida Tech zigzag boards were mounted (one board at a time) on a BNL 10 cm × 10 cm triple-GEM detector and were scanned with X-rays at BNL by Bob Azmoun and Mike Phipps. The gas gaps of the detector were 5.63/1.34/1.54/1.53 mm and Ar/CO_2 70:30 was used.

For each board, scans were performed along the azimuthal direction at three different R coordinates. At each R, a 10 mm range was scanned with a 0.1 mm step; in each run

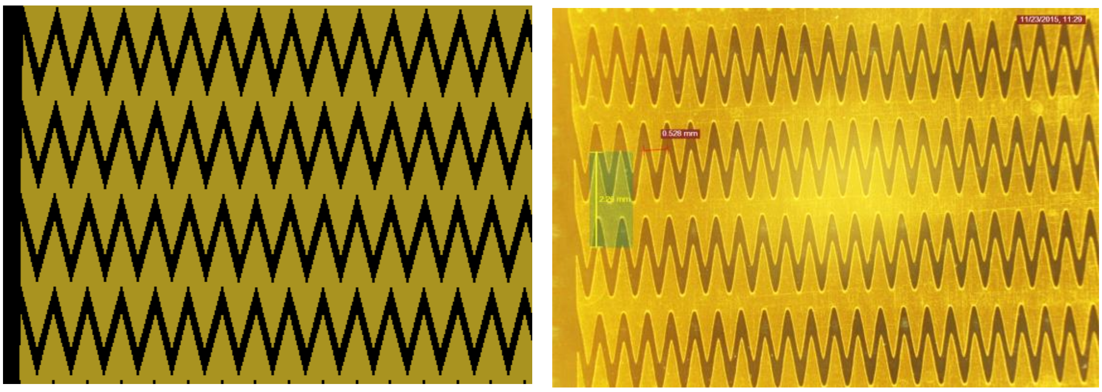

Figure 17 Zigzag strips as originally designed (left) and as actually produced by a PCB factory (right) for the 48-strip board. On the right picture, the two indicated dimensions are: strip pitch (vertical tip to tip distance) 2.26 mm and zigzag period (horizontal tip to tip distance) 0.528 mm.

5k events were collected. The drift field in this configuration was 1 kV/cm, transfer and induction fields were 3 kV/cm. The detector was read out with an APV25 chip and data were taken with the Scalable Readout System (SRS). The detector was operated at higher gas gain for most of the runs, which unfortunately caused APV saturation. Only 30 runs for the 30-strip board were taken at lower gain. Looking at the data, we observe that the hit position reconstructed with the centroid method is not a linear function of the X ray position (Figure 18). In certain regions near the "spine" of the strips, corresponding to the flat parts on the curves in Figure 18, the readout is actually not sensitive to the X-ray positions. It is unclear if that was entirely due to the intrinsic behavior of the zigzag readout or if it is related partially to a saturation of the APV25 chips.

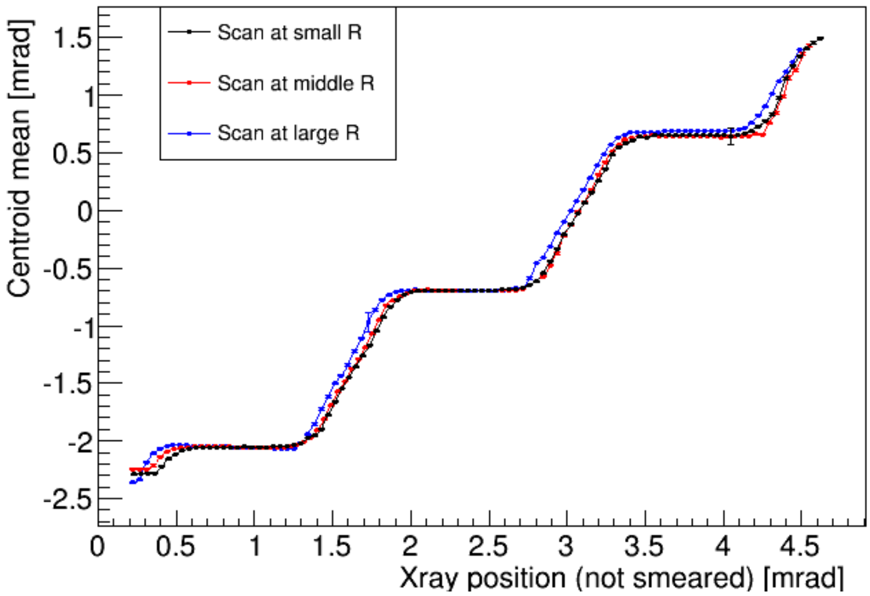

Figure 18 Measured hit centroid vs. X-ray position on the 30-strip board. Note that the X-ray position is not aligned so that the curves are not diagonal.

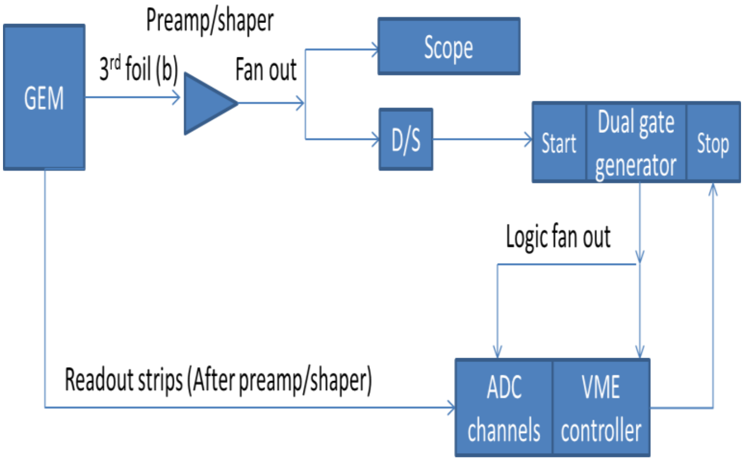

Figure 19 Setup for scanning zigzag readout boards with Struck ADCs at BNL.

In order to avoid saturation effects, Aiwu Zhang scanned the two zigzag boards at BNL again in November using individual preamp/shaper circuits and three VME-based ADCs (Struck SIS 3300/3301) with larger dynamic ranges. Each ADC has 8 channels with two of the ADCs providing 12-bit resolution and the third ADC allowing 14-bit resolution. Figure 19 shows the logic of using the Struck ADCs for reading out the detector. Each channel was calibrated by injecting a test pulse into the preamplifier; all channels showed very good linear response and large dynamic range, so that saturation was not a problem anymore. Figure 20 shows a typical calibration curve for one of the ADC channels, which allowed us to measure the actual full charge of a signal.

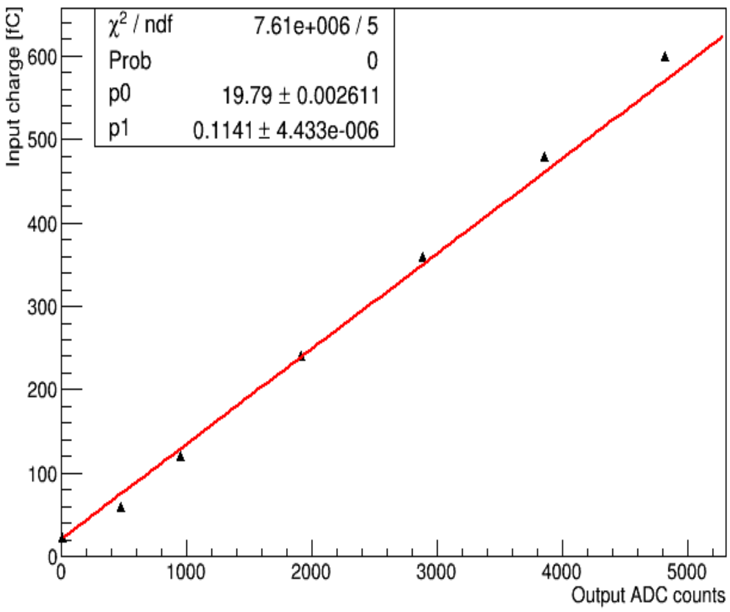

Figure 20 Calibration curve for the first channel of the 14-bit Struck ADC.

Table 1 Scan scenarios for the different readout boards at BNL.

Gas gap configuration	Readout strips	Applied voltages and fields	Scanned scenarios
15.6/1.7/ 1.7/2.2 mm	COMPASS-style 2-D straight strips	E_d=0.75 kV/cm E_t=E_i=3 kV/cm V_{GEM}=380V	Along X: 41 runs with 100 μm step; 35 runs with 50 μm step.
			Along Y: 61 runs with 100 μm step; 25 runs with 50 μm step.
3/1/2/1 mm	30 radial zigzag strips	HV divider: 1/0.5/0.5/0.45/1/0.45 /0.5 MΩ	Along X: 38 runs with 100 μm step.
			Along Y: 21 runs with 100 μm step; 10 runs with 100 μm step at another φ coordinate on the board.
3/1/2/1 mm	48 radial zigzag strips	Ditto.	Along X: 51 runs with 100 μm step.
			Along Y: 21 runs with 100 μm step.

In Table 1, we summarize the scans that were performed by Aiwu Zhang in November with help from our BNL colleagues. We first took data with a standard 2D COMPASS readout board where the gas gaps of the GEM detector had a non-standard 15.63/1.70/1.69/2.16 mm configuration. These data were mostly used for commissioning the system and the GEM detector. Then we scanned the 30-strip and 48-strip zigzag boards using the GEM detector with standard 3/1/2/1 mm gas gaps. These scans were done along the standard X and Y directions of the scanner. Scans along X were across the zigzag strips in azimuthal direction; scans along Y were along the zigzag strips in R direction. We took 10k events for each point to ensure sufficient statistics for analysis.

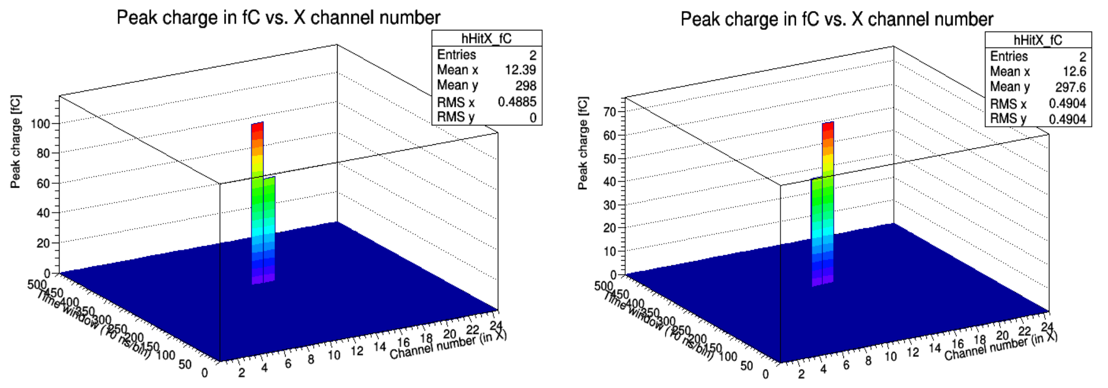

Figure 21 Measured pulse charges in two typical events when aiming the X-rays between two strips on the 30-strip zigzag board.

We have taken a very first look at the November data with an online monitoring program. Figure 21 shows two typical events from one run when the X-rays were aimed at a position between two strips. These events mostly have a strip multiplicity of two as expected. For the same run, we observe a charge spectrum with distinct photopeak and escape peak on one strip (Figure 22, left), but we find only one peak on the other strip (Figure 22, right). When the X-ray position is closer to the strip on the left, more charge is induced on that strip and the deposited energy appears to be better resolved. We observe that the situation is reversed when the X-ray gun is moved ~0.5 mm to the right. Then the main peak and escape peak appear in the spectrum for the right strip, but only one peak appears in the spectrum for the left strip.

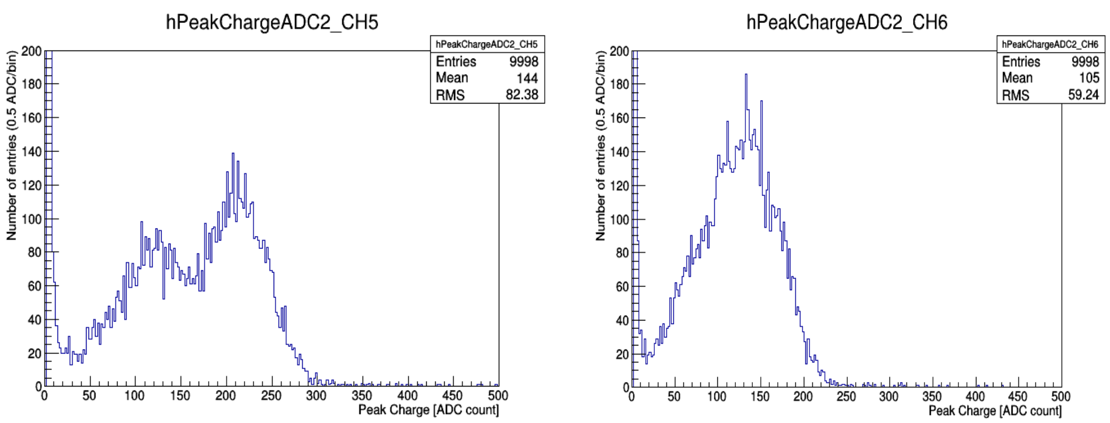

Figure 22 The spectra measured by the two individual strips in a run for the 30-strip board.

Stony Brook University:

The results of the successful tests and its performance of the RICH prototype in two test-beam campaigns have been published in an IEEE-TNS publication and the results were presented at the 2015 IEEE Nuclear Science Symposium.
Working on refurbishing the evaporator has begun. In the initial stage it was estimated how well the vacuum has to be in order to reliably perform evaporation of MgF_2 on mirror blanks. This will determine the type and power of vacuum pumping for the evaporator. We are discussing and sketching with local workshop experts modifications to the housing of the evaporator for inserting larger mirror blanks with minimum breach of vacuum, e.g., by introducing an antechamber. In addition, investigations about supporting and moving the larger mirror blanks within the evaporator to obtain a homogenous deposit of the protective and dielectric layer are ongoing and the acquisition of instrumentation to monitor the deposit process. The idea of smoothing surface areas due to unevenness of layer deposition with the help of ion bombardment has been introduced and is being looked after.

University of Virginia:

- **Published paper:** Our paper on the performances in test beam of the EIC-FT-GEM prototype I was submitted in September 2015 to NIMA and published in November 2015.
  K. Gnanvo et al., ***"Performance in Test Beam of a Large-area and Light-weight GEM detector with 2D Stereo-Angle (U-V) Strip Readout",*** Nuclear Inst. and Methods in Physics Research, A 808 (2016), pp. 83-92.

  The paper report the results from the analysis of the FTBF test beam data in terms of the response uniformity and efficiency higher than 95% over the large area chamber, with a measurement of the angular resolution of 60 μrad in the azimuthal direction and position resolution better than 550 μm in the radial direction, achieved with the U–V strip readout.

- **The common GEM foil design:** The collaboration with Florida Tech and Temple University on the common GEM foil design for EIC-FT-GEM prototype II is still ongoing and very active.

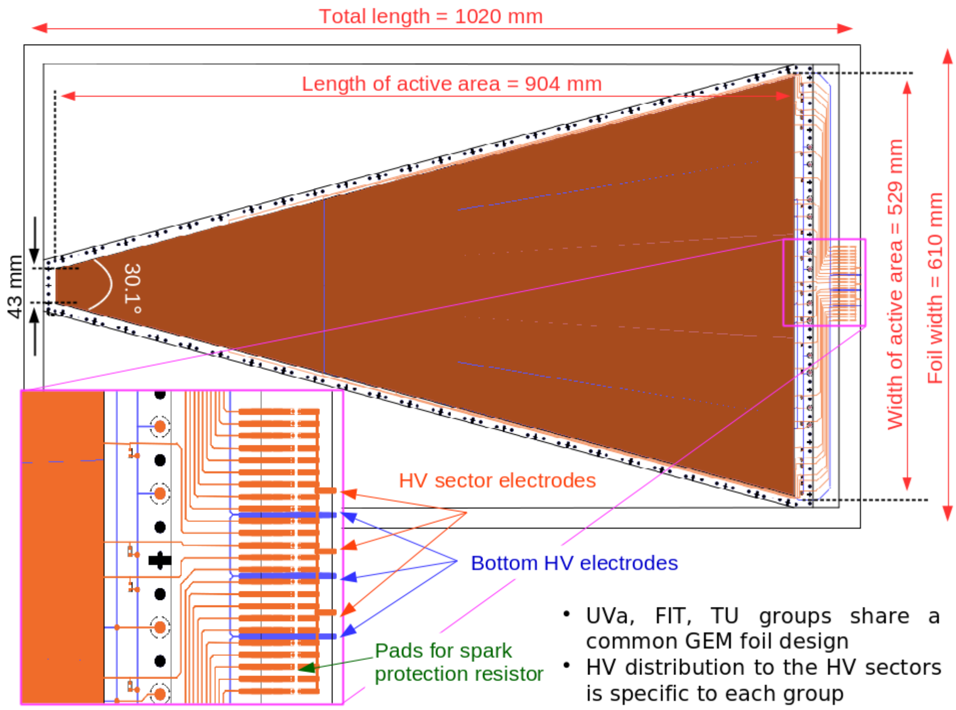

Figure 23 Common EIC GEM foil with the UVa HV electrode scheme.

The common GEM foil design was submitted to the expert at CERN PCB workshop for validation. Suggestions from CERN experts were implemented and finally, the GEM holes scheme was added. The design is now completed and the common GEM foil is ready for fabrication. Figure 23 shows the picture of the Gerber file of the common GEM foil with an emphasis on the UVa implementation of the HV electrodes and protective resistances.

- **2D U-V strips readout:** The left picture of Figure 24 shows the basics parameters of the new readout board. The board is a flexible double-layer printed circuit board (PCB) with a U–V strip pattern, based on the same 50 µm thick copper-clad

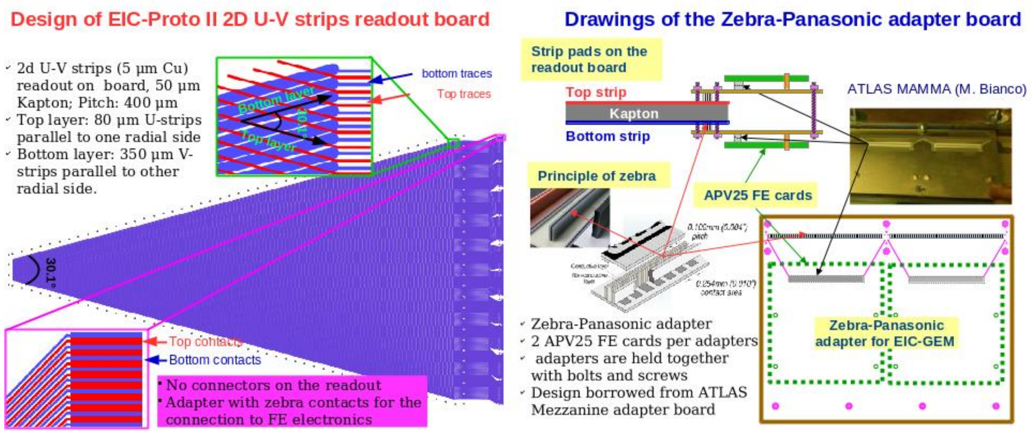

Figure 24 (Left): U-V strips readout board for EIC-FT-GEM prototype II. (Right): Design of the Zebra-to-Panasonic adapter board.

polyimide material used to produce the GEM foils. The strips of the top layer (U-strips) run parallel to one of the two radial sides of the detector and the strips of the bottom (V-strips) layer are parallel to the other side.
The readout design is an upgrade of the one used in the EIC-FT-GEM prototype I but has narrower pitch (400 µm versus 550 µm), top strips width (80 µm vs 140 µm) and bottom strip width (350 µm vs 490 µm). With the smaller pitch and strip widths, we expect to achieve better angular resolution in the radial direction. In addition, the stereo angle between U and V strips is larger (30.1° vs. 12°) than for the previous readout; which would also lead to an improvement of the spatial resolution in the azimuthal direction.

- ✔ **Zebra-to-Panasonic adapter board:** Another specificity of the new board is the electrical contacts to the front end electronics of all top and bottom strips is done on the outer radius side of the detector. By avoiding FE electronics from inner radius side and the radial sides of the chamber, we protect the electronics from intense radiation near the beam pipe and also prevent multiple scattering from the FE card material in the active area of the forward tracker. In addition, in the new readout board, the electrical contact between the strips and the FE electronic channel is done using zebra connectors. Zebra connectors are commonly used for electronic devices such as liquid crystal displays (LCDs) to provide solder-less electrical connection between the LCD and PC board or other type of board-to-board connections. The principle of zebra connectors is illustrated right sketch of Figure 24. With this type of electrical contact, no connectors are mounted on the readout board, making it easier for production and more operation. A zebra-to-Panasonic adapter board is under designed for the connection of the detector readout to the 130-pins Panasonic connectors of SRS-APV25 FE cards. The preliminary drawing of the zebra-to-Panasonic adapter board is shown on right picture of Figure 24. Each board will host 2 APV25 FE cards to readout a total of 256 channels. In the current design two adapter boards will be attached together face to face with the readout board strip pads sandwiched between the zebra connectors. Screws are used to keep the two adapters together and ensure good electrical contact of the zebra with the readout strip contacts.

- **Chromium GEM foil (Cr-GEM):** We have continued to study of GEM foil with

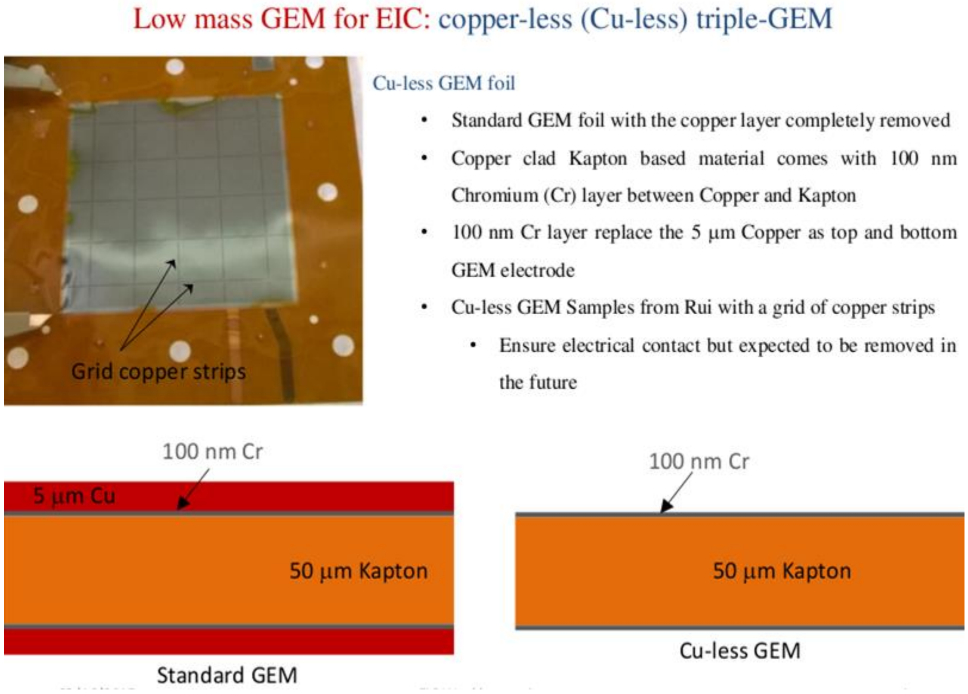

Figure 25 Chromium GEM foil (Cr-GEM) for low mass triple GEM detectors.

100 nm Chromium layer replacing the 5 μm Cu layer used as top and bottom electrode of standard GEM foil. Cr-GEM foil is a good candidate for lightweight and low mass triple GEM detector such as the one used for EIC forward trackers. Description of Cr-GEM foil is shown on Figure 25.

The impact of Cr-GEM low mass on the material budget of a light weight triple

Triple-GEM with standard GEM foil

	Quantity	Thickness μm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Kapton	2	25	1.42	286	1	0.0175	0.0071
Drift							
Copper	1	5	8.96	14.3	1	0.0350	0.0045
Kapton	1	50	1.42	286	1	0.0175	0.0071
GEM Foil							
Copper	6	5	8.96	14.3	0.8	0.1678	0.0215
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
Grid Spacer							
G10	3	2000	1.7	194	0.008	0.0247	0.0082
Readout							
Copper-80	1	5	8.96	14.3	0.2	0.0070	0.0009
Copper-350	1	5	8.96	14.3	0.75	0.0262	0.0034
Kapton	1	50	1.42	286	0.2	0.0035	0.0014
Kapton	1	50	1.42	286	1	0.0175	0.0071
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Gas							
(CO2)	1	15000	1.84E-03	18310	1	0.0819	0.0028
					Total	**0.471**	**0.090**

Triple-GEM with Cr-GEM foil

	Quantity	Thickness μm	Density g/cm3	X0 mm	Area Fraction	X0 %	S-Density g/cm2
Window							
Kapton	2	25	1.42	286	1	0.0175	0.0071
Drift							
Copper	1	0	8.96	14.3	1	0.0000	0.0000
Kapton	1	50	1.42	286	1	0.0175	0.0071
GEM Foil							
Copper	6	0	8.96	14.3	0.8	0.0000	0.0000
Kapton	3	50	1.42	286	0.8	0.0420	0.0170
Grid Spacer							
G10	3	2000	1.7	194	0.008	0.0247	0.0082
Readout							
Copper-80	1	0	8.96	14.3	0.2	0.0000	0.0000
Copper-350	1	0	8.96	14.3	0.75	0.0000	0.0000
Kapton	1	50	1.42	286	0.2	0.0035	0.0014
Kapton	1	50	1.42	286	1	0.0175	0.0071
NoFlu glue	1	60	1.5	200	1	0.0300	0.0090
Gas							
(CO2)	1	15000	1.84E-03	18310	1	0.0819	0.0028
					Total	**0.235**	**0.060**

About 50% reduction in the amount of material in a EIC-FT-GEM with Cr-GEM

Figure 26 Comparison of the radiation length of triple-GEM with Cr-GEM foil and standard GEM foil.

GEM detectors is shown Figure 26. A comparison with standard GEM shows up to 50 % reduction of the material in the active area of the triple-GEM. This is because in lightweight triple-GEM detector such as the material budget is dominated by the GEM foils and readout board all made of the same copper-clad Kapton foil.

Tests of Cr-GEM foils: We recently built a small triple-GEM prototype with Cr-GEM foils purchased from CERN workshop. A picture of the foil is shown on Figure 25.

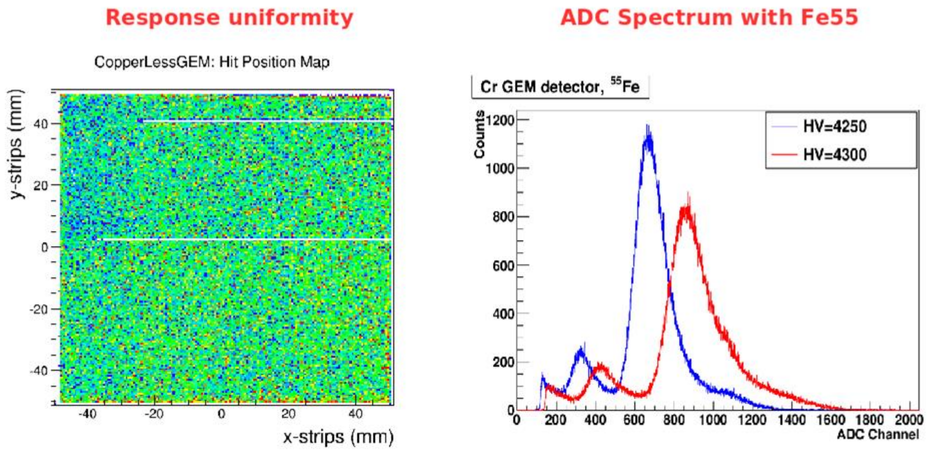

Figure 27 Characterization of triple-GEM detector with Cr-GEM foils.

Results on Figure 27 show that the good response uniformity of the Cr-GEM prototype with cosmics. The spectrum (in ADC units) of ^{55}Fe sources with the characteristic escape peak is shown for two different gain (HV). The Performances of the Cr-GEM prototype are very similar to what we would expect from a detector with standard GEM foils. We are currently testing the prototype in our x-ray box to study the long term stability under very high rate and discharge probability with heavily ionizing particle. Early signs of degradation in the performance of the prototype with the apparition of dead area have been observed under intense radiation. The degradation may have been caused by ageing or impact of spark discharges. The high rate test with x-ray source is ongoing and we are investigating the long term performance of such GEM foils.

Yale University:

3-Coordinate GEM
Analysis code was recovered from a major computer failure and analysis is near completion.

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas
A large range of measurements have been made on several 10 cm x 10 cm chambers with different readout plane geometries and different gas mixtures. These results were presented at Quark Matter 2015 and at IEEE/NSS/MIC 2015. A paper draft is in hand and is in final editing. Two key figures from the paper showing energy resolution vs Ion Backflow (IBF) are shown in Figure 28 and Figure 29. In these figures each curve represents a different gas mix. The points along a given curve represent a scan of the MMG in steps of 10 V starting at the voltage where the MMG gain is 200. For each point the GEM voltages are adjusted to keep the total chamber gain at 2000.
We have acquired two MMG with a pad plane readout with resistive strips printed on an insulating layer over the pads. The first measurements show that the MMG can operate at higher voltage and gain than MMG with no resistive layer. Discharges have much lower voltage drop on the MMG mesh and much smaller current flow to the

anode. At high ionization loading however, the chamber appears to have corona-like discharge. We are still investigating this phenomenon.
We have acquired all wire planes and built an extended gating grid structure over a 10

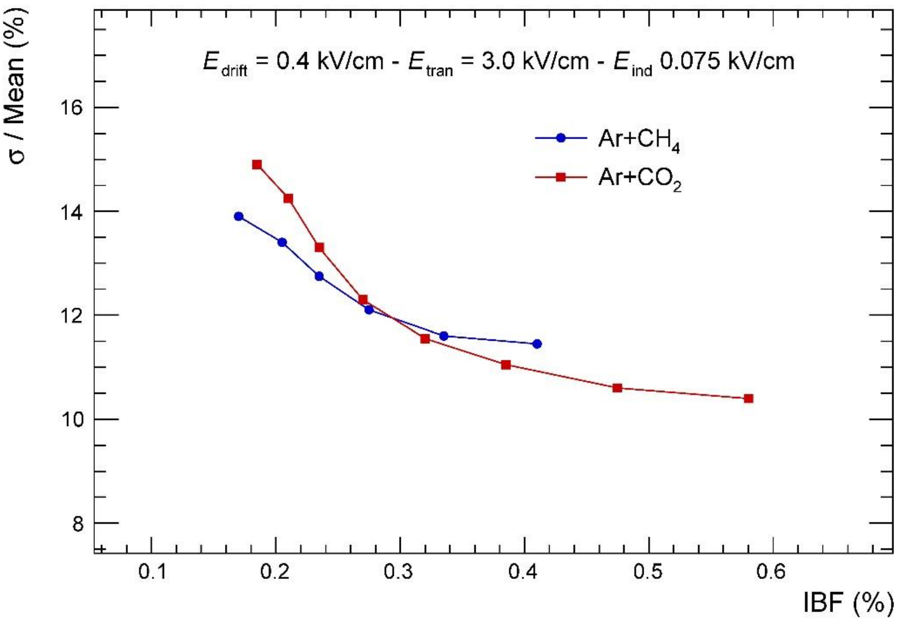

Figure 28 Energy resolution (σ of ^{55}Fe peak) vs Ion Back Flow (IBF) for Argon gas mixes.

cm × 10 cm wire chamber. Initial baseline measurements to determine electron and ion transparency as a function of voltage settings on the grid elements are underway.

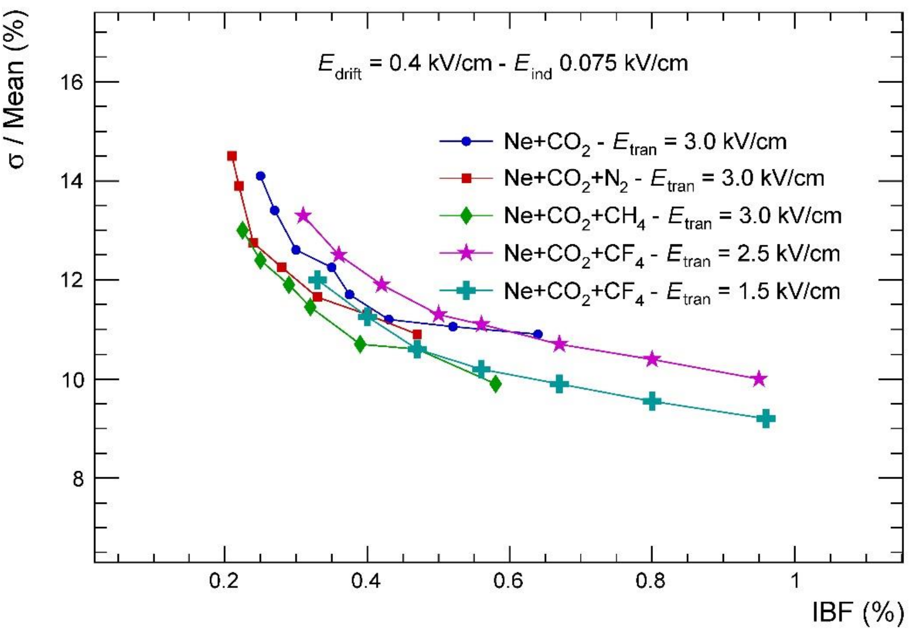

Figure 29 Energy resolution (σ of ^{55}Fe peak) vs Ion Back Flow (IBF) for Neon gas mixes.

What was not achieved, why not, and what will be done to correct?

Brookhaven National Lab:

We did not finished testing all of the gases we would like to consider using for future TPC and TPC/Cherenkov operation. We encountered some difficulties in testing some of them, such as Ar/CF_4 (95/5), in terms of stability of operation of the GEM detector. We also had some breakdown problems when attempting to measure the drift velocity. This may be due to impurities in the particular gas we are using, which we intend to investigate. We will also test more CF_4 rich mixtures which may provide more stable GEM operation. We also plan to study gas mixture containing neon, which would provide lower positive ion feedback for the TPC.
We have not yet tested the detector with Cherenkov GEM. The first of these tests will be to install the GEM along with its mesh on its movable stage and study any possible high voltage problems that may occur as the GEM is brought into close proximity to the field cage of the TPC. After we have investigated the electrostatic interaction of the Cherenkov GEM with the TPC, we will install the CsI photocathode on the Cherenkov GEM and begin testing the Cherenkov portion of the detector. This will require making CsI photocathodes, which we plan to do with the help of our colleagues at Stony Brook. We plan to begin all of these tests starting in January of 2016.

Florida Tech:

We achieved most of what we had planned for this period, except measuring the performance of a GEM detector with zigzag strips in a magnetic field and writing a paper on examining the geometric mean method for resolution studies. These tasks were delayed because we decided that it was more important to perform the X-ray scans at BNL first in preparation for the construction of the next large FT GEM prototype.

Stony Brook University:

It turned out that the optimization of the pad structures for the RICH readout with the help of charge dispersion is not feasible. The smallness of the charge signal due to HBD-like photon readout in CF_4 would require to decrease the pad size. Even with charge dispersion the RICH would not benefit from 2 mm pixels as they are already near the diffusion limit. A new approach for improving the position resolution to measure precisely the Cherenkov-ring diameter is attempted which will be described in the next section.

University of Virginia:

- The design and drawings of the support frames for the GEM foils and for the mechanical structure of the detector have been put on hold while we were working on finalizing the GEM foil and readout board. With this task completed, we are ready to start working on the frames design and planning for the actual assembly of the prototype.
- The discussion with Tech-Etch or CERN concerning the production of large size Cr-GEM has not started yet since we are still performing the high radiation tests of

the small Cr-GEM foils and studying in detail study the ageing properties and robustness against spark of this new type of GEM foil. It is essential that we fully investigate the performances and characteristics of Cr-GEM with small size prototype to better understand its properties before we move to larger size for an EIC prototype.

<u>Yale University</u>:

3-Coordinate GEM
Final analysis was delayed by computer problems but is now again underway.

Hybrid Gain Structure for TPC readout – 2 GEM plus Micromegas
Publication of the results for the hybrid gain structure in different gases is a few months behind schedule but final editing of the paper is in progress.

Future

> What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

Overview

Dr. Alexander Kiselev (BNL) performed the following studies for readout patterns that might improve the charge sharing and consequently position resolution for the projects described within this report.

The analysis of both FIT and BNL zigzag GEM tracking detector data, collected during Fall'2013 test run at FNAL, revealed a number of issues with the present readout board designs:

- strongly non-linear behavior of the measured residuals after weighted mean centroid calculation as a function of charged particle track coordinates across the strip direction

- the noticeable dependence of the required differential non-linearity (DNL) correction on the electron cloud charge footprint size

- existence of several hundred micron wide regions around zigzag strip centers with almost no sensitivity of the weighted-mean- centroid-based coordinate to the actual charged particle track location

It was realized at some point, that all these problems may have the same origin, namely be directly linked to the suboptimal effective charge sharing between neighboring strips in both FIT and BNL designs. The idea emerged to set up a simplified simulation environment to 1) confirm this explanation and 2) possibly come up with a better readout board design, which could reduce or (ideally) eliminate the above mentioned drawbacks.

This environment was realized as a standalone set of ROOT scripts on top of a collection of custom C++ classes, which allowed one to model the idealized charge collection process by GEM readout plane strips. A number of essential simplifications were used at this stage: 1) it was assumed, that spatial distribution of the electron cloud right below the „bottom" GEM foil has a pure 2D gaussian shape, 2) ~100% of the readout plane can be covered with electrodes, so that no electric field distortions need to be taken into account. Pedestal noise was simulated on per-strip level as an additive quantity with 0 mean and known gaussian sigma.

Despite the simplicity of this simulation environment it was perfectly sufficient to describe, at least qualitatively, the features of weighted mean centroid calculations in the real data, which were mentioned above, in particular the strong DNL effects and sensitivity to the charge cloud footprint size. Figure 30 shows uncorrected residuals after weighted mean centroid calculation as a function of track coordinate across the strip direction for FIT-like zigzag design for electron cloud footprint sizes of 200 and 600 microns (gaussian sigma). It is clearly seen, that the residuals exhibit a strongly

non-linear dependence on the coordinate, which is different for different electron cloud sizes.

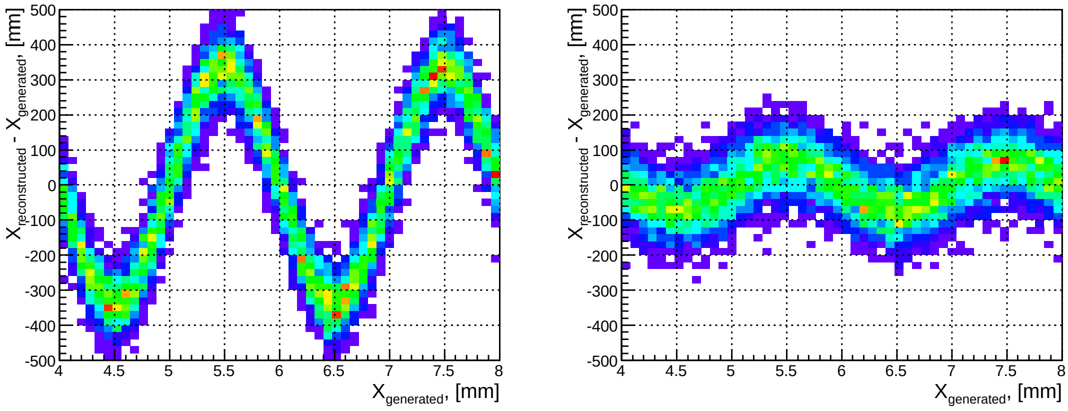

Figure 30 A systematic DNL of uncorrected weighted mean residuals for FIT-like strip geometry as a function of simulated electron cloud coordinate in the direction across the strips. Horizontal axis covers 4mm range (two strips) in both plots. Strip center locations are at 4mm, 6mm and 8mm. Left panel: charge cloud footprint size 200 microns (gaussian sigma). Right panel: the same, but charge cloud footprint 600 microns.

It was also shown, that there exists a unique „linear“ charge collection scheme (and respective idealized hardware zigzag strip geometry, see left panel in Figure 31) which does not show any DNL for a straightforward 3-strip weighted mean centroid in a wide range of charge cloud footprint sizes for a given value of strip pitch (see left panel of Figure 32) As such, this scheme also 1) does not exhibit any „position insensitive“ areas

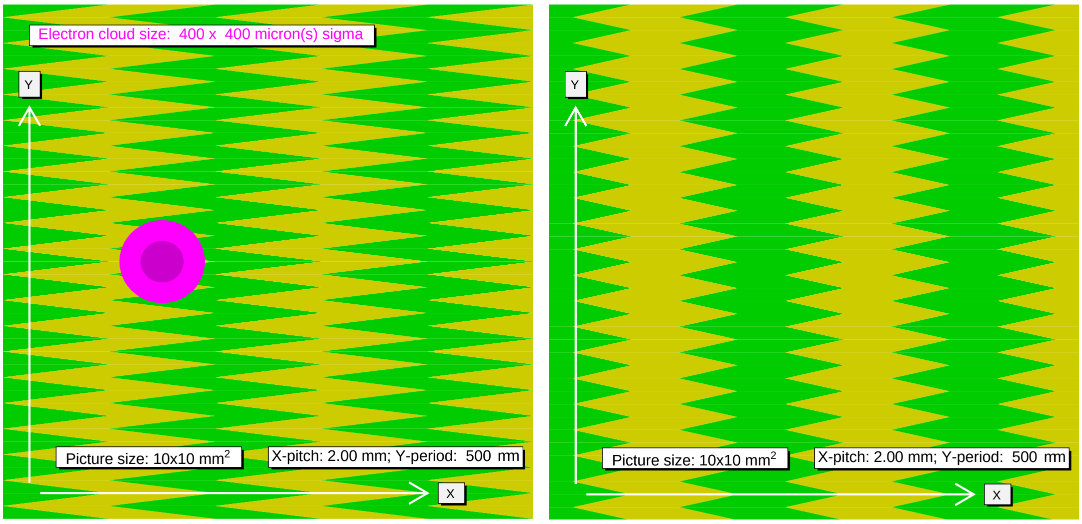

Figure 31 A schematic layout of a 10x10mm^2 area of the GEM readout board equipped with zigzag strips. Pitch 2mm as indicated. Alternating green and yellow colored vertical zigzag bands show effective electron cloud collection areas of neighboring strips. A 1σ and 2σ circular areas corresponding to a gaussian electron cloud footprint size of 400 microns are indicated in pink. Left panel: "ideal" geometry (zigzag "tips" reach exactly the centerlines of the neighboring strips). Right panel: FIT-equivalent geometry with "understretched" zigzag strips and wide areas around strip centers with poor charge sharing (and as a consequence almost no sensitivity to a charged track location).

around strip centers and 2) gives very similar expected spatial resolution values at the strip centers (minimal charge sharing) and in the inter-strip regions (charge sharing ~50/50 between neighboring strips). It should be mentioned, that a very similar layout was realized in the LEGS TPC readout board.

The essential interplay between basic parameters like pitch *across* the strip direction, noise level, periodicity of the geometry *along* the strip direction, charge cloud footprint size was also investigated in detail. In particular, right panel of Figure 32 shows, that in a simplified gaussian model the average expected spatial resolution linearly depends on the pedestal noise level.

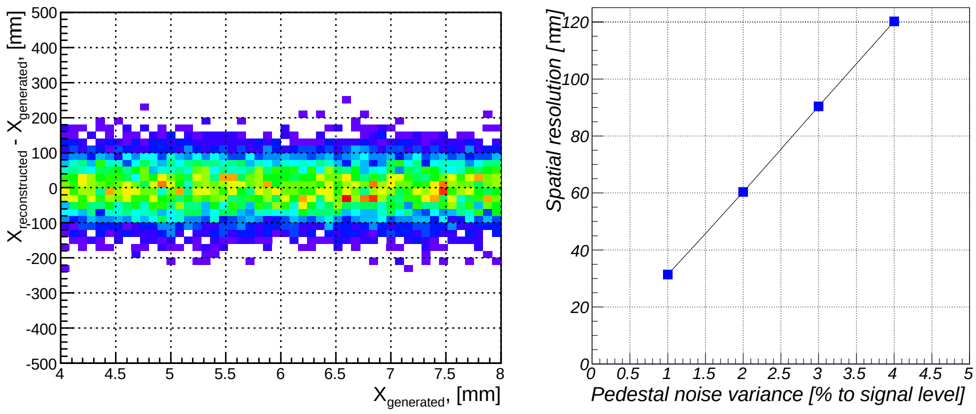

Figure 32 Left panel: same as Figure 30 (left), but for the "linear" charge sharing geometry model, corresponding to the strip layout shown in the left panel of Figure 31. Weighted mean centroid over 3 neighboring strips clearly gives unbiased estimate of the simulated cloud center location. Right panel: expected average spatial resolution of the "linear charge sharing zigzag" as a function of pedestal noise.

Possible application of the „linear charge sharing" scheme to more sophisticated readout board designs, in particular the 2D ones with both strip and pad „basic" elements, was also investigated to a certain degree.

It is assumed, that the next round of simulations will be focused on a more realistic modeling procedure of the readout board layouts (and the complete GEM foil stack if needed) using available Open Source programs and libraries, including *Elmer* electrostatic calculation code in conjunction with the *Gmsh* 2D and 3D meshing tool, *Garfield++* together with *Magboltz* and (should it becomes needed) *gerbv* library in order to export essential parts of the models as gerber files suitable for PCB manufacturing. To this moment a feasibility study of the outlined path was performed and no obvious show-stoppers identified. Should this procedure succeed, this may in principle open a way to establishing a de-facto „layout standard" for the low-channel-count and easy-in-analysis 1D and 2D GEM readout boards.

<u>Brookhaven National Lab:</u>

Our main activity during the next funding cycle will be to continue our tests of the TPC-Cherenkov prototype detector. We will complete our study of various gases for the detector, measuring drift velocities, studying their operation with the GEMs, studying ion back flow, etc., and determine the best operating gas for TPC/Cherenkov operation. We will also investigate the electrostatic interaction of the Cherenkov GEM and the TPC and determine the optimal operating configuration for the two detectors. We will then install the CsI photosensitive GEM in this position and begin testing the Cherenkov portion of the detector. Assuming all of this procedure goes successfully, we hope to be

able to test the full combined TPC/Cherenkov detector in the test beam at Fermilab in the spring of next year.
In addition to these tests, we also plan to investigate new and improved readout patterns for the chevron strips. As discussed in a separate part of this report, we have already begun to investigate these patterns with calculations and simulations. Using this information, we plan to fabricate new readout boards with a number of different readout patterns that we can measure and study in the lab. We hope that this will lead to better position resolution and improved linearity with the chevron readout for the TPC.
We also plan to study hybrid configurations of GEMs and Micromegas which can reduce ion feedback for the TPC and thereby reduce space charge distortions. We intend to work with the Yale group on this project, which has had considerable experience in this area as well as on other TPCs.
The study of the TPC/Cherenkov detector is part of the original R&D plan for the BNL group. However, the investigation of the new chevron patterns and the study of the combined GEM/Micromegas operation is a new activity for our group, although we have already had several preliminary discussions about GEM/Micromegas operation with the Yale group.

Florida Tech:

We will analyze the new BNL scan data obtained for the zigzag boards.
Before producing the new large zigzag readout board for the next FT GEM prototype, we want to demonstrate that the re-designed zigzag strips have a more linear response. To that end, we plan to produce new radial zigzag boards for a 10 cm × 10 cm GEM detector with the re-designed zigzag pattern and will scan them at BNL in early 2016 in a similar fashion as described above.
We will start producing the large common GEM foils and send out the designs for drift and readout foils and the various frames for quotes. We will also attempt to get them produced if that is feasible on the time frame of the next 6 months. We will investigate stiff carbon fiber frames for assembling the next EIC FT GEM prototype.
We need to finish our second paper on the “Study of the Geometric-Mean Method for Determining Spatial Resolution of Tracking Detectors in the Presence of Multiple Scattering” and submit it to a peer-reviewed journal.

Stony Brook University:

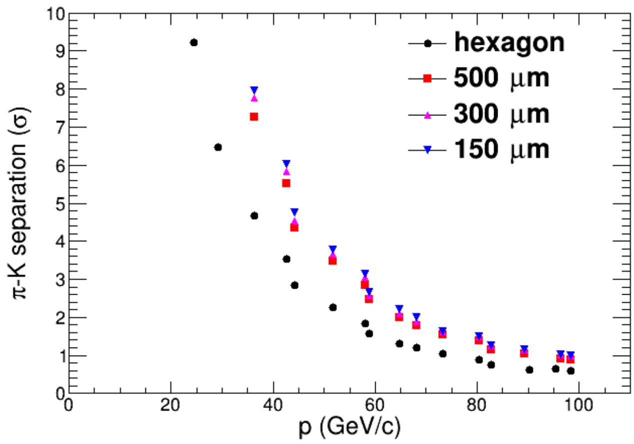

Figure 33 Separation power for various readout point resolutions.

The charge cloud for a single photo-electron in the RICH is quite small due to the small diffusion coefficient in the radiator gas CF_4, of about 150 μm. This means that the

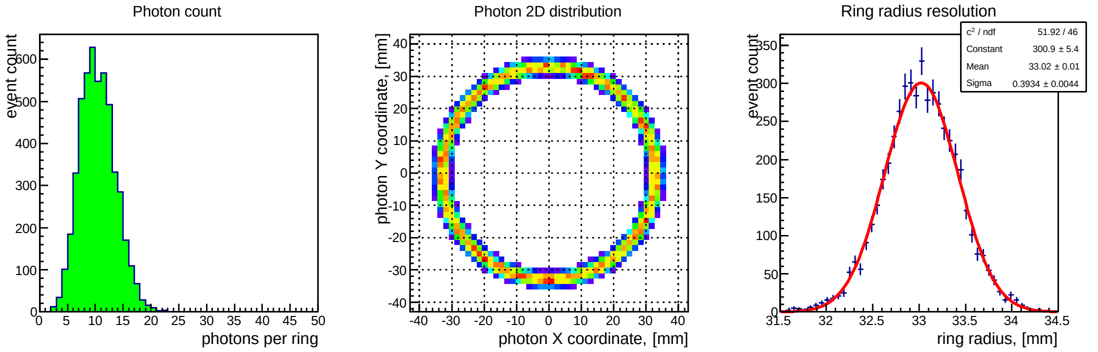

Figure 34 Simulated parameters with input from measurements at test-beam campaigns (A. Kiselev).

charge cloud is too small for geometrical charge division for the pad size that has been used and limits significantly the position resolution for the ring measurement and therefore limits the power of particle separation (see Figure 33 and Figure 34). The obvious solution is either to decrease the pad size which in turn means a higher channel count; or to increase the signal width which cannot be achieved with the radiator that will be used. A further solution is to introduce a charge sharing by means of interleaving channel pattern and at the same time leaving the pad size the same.

Dr. Alexander Kiselev from the BNL group proposed a pattern structure as can be seen in Figure 35 and performed an extensive study about the properties and response of zig-zag like read-out structures applied to various applications. Among them are hexagonal pads as have been used in the previous test-beam campaigns for the RICH prototype to modify such that interleaving patterns occur across neighboring pads. The result would be that the charge cloud due to a photo-electron would always hit an area which is contained by a small hexagon with 1.25 mm apothem, half the size of a regular hexagon as used in the test-beam. As estimated in Figure 36, this would gain a factor 2 in ring radius resolution and at the same time leaving the overall pad size the same, i.e., having the same channel count.

We are planning to design a pad readout board with snowflake pattern, locally at Stony Brook with engineers and aiming for placing an order to our previous PCB vendor. The next steps would be then to perform basic tests with this readout pattern and it is

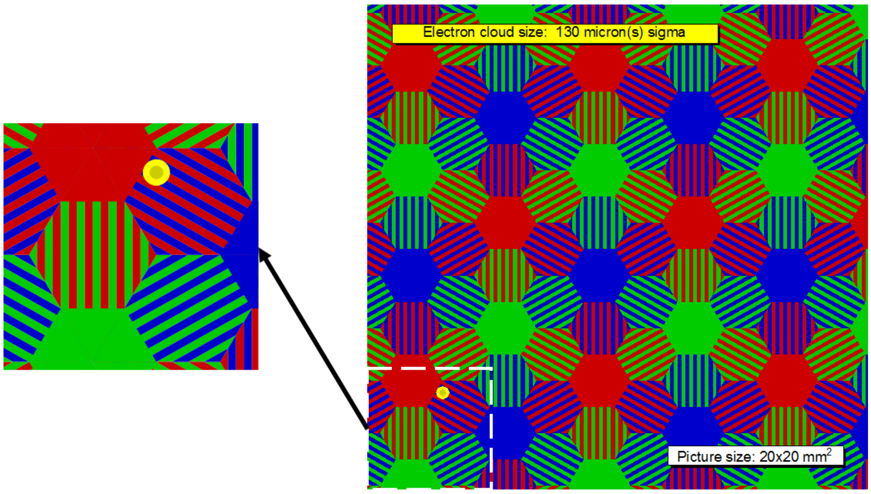

Figure 35 Interleaving pattern for hexagonal readout pad with zoomed in area on the left (A. Kiselev).

foreseen to test it further in a future test-beam campaign, preferably at Fermilab. Compared to the original plan of using charge dispersion as a way to improve the position resolution for the Cherenkov ring measurements a new approach has been started and will be pursued in the next funding cycle.

The other project to be continued is the refurbishment of the Big Mac evaporator after finalization of design consideration so that the necessary equipment for the mirror

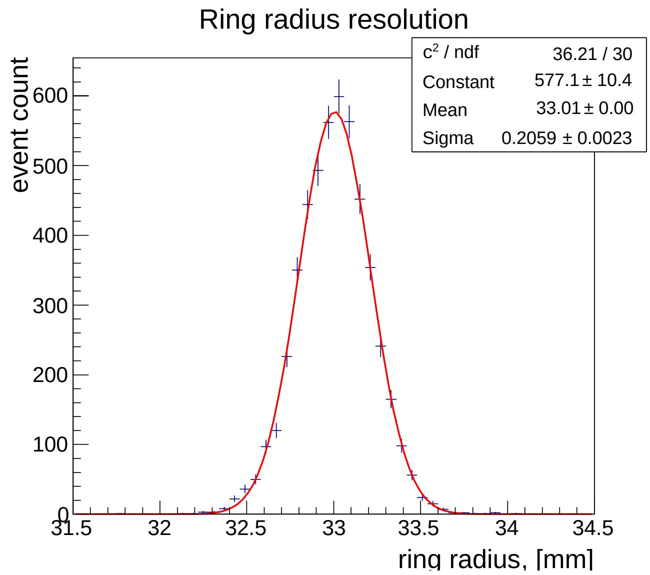

Figure 36 Ring radius resolution for an interleaved pad structure (A. Kiselev).

production can be purchased. Figure 37 shows the evaporator vessel that is being prepared for modification. The diameter of the vessel is about 7 feet and therefore allows the insertion of large sized mirror blanks as described above for evaporating with MgF_2. Due to the complexity of the process and the large volume careful calculations and considerations are being performed.

Figure 37 Large size evaporator "Big Mac" at SBU.

University of Virginia:

For the coming cycle from January 2016 to June 2016, we plan to:

- Continue the tests of the Cr-GEM detector in x-ray box to study the performance under severe background conditions
- Complete the design of the Zebra-to-Panasonic adapter board and of the GEM frames and mechanical structure of the triple-GEM chamber
- The new 2D U-V strips readout design with narrow strips present several advantages that are beneficial for EIC tracking detectors. However a few new ideas such as etching the top and bottom strips contacts on the same Kapton support as well as the zebra connectors for electrical contacts need to be tested before we produce the EIC-size board for the second prototype. We plan to develop a small (10 x 10 cm^2) 2D U-V strips readout board with the new zebra-based connection scheme and zebra-to-Panasonic adapter and perform validation tests.

Yale University:

3-Coordinate GEM
In the coming year we will complete the analysis and publish the results.

Hybrid Gain Structure for TPC readout
A draft paper is in hand on the present results and we expect to submit the paper this year. We will continue investigation of the 2-GEM+MMG structure with resistive planes and investigation of the extended gating grid concept.

What are critical issues?

Brookhaven National Lab:

The main critical issue is to demonstrate that the TPC and Cherenkov detectors can be operated as a combined detector. We have successfully demonstrated that the TPC operates well, but we must now demonstrate that it can be operated simultaneously with the Cherenkov. The first step will be to show that the Cherenkov operates in a standalone mode and then in combination with the TPC. We plan to do this by performing various tests in the lab as described above, which would then be followed by a beam test to demonstrate that the combined detector is fully operational.
Another critical issue that remains is that we need to obtain appropriate readout electronics for the TPC. We will initially use the SRS readout system for the TPC, but it has many limitations as a final readout system. We plan to investigate the T2K readout electronics as a possible system that could at least be used to fully test our prototype, but we are not sure that it would be suitable for a final readout system for an EIC detector. Another possibility is the readout system based on the SAMPA chip that is being developed for ALICE. This system is not currently available for us to use or test, but we will also explore it as a possibility for the future.

Florida Tech:

We had transferred Gerber files for the common GEM foil design to the CERN workshop for adding the actual GEM holes into the design. As of mid-October that step was completed and from the technical point of view we were then ready for placing a corresponding order of GEM foils with the CERN workshop. Unfortunately, we have been forced to hold off on actually ordering the production of these foils at CERN because as of the writing of this report (third week of December 2015) the funds that were allocated for this production after the June 2015 review, have not yet arrived at the universities (Fl. Tech and U. Va.) from BNL.
A critical issue specifically for Florida Tech is the continued availability of our post-doc Aiwu Zhang throughout the production and testing phase for the next FT prototype. The significant progress at Florida Tech described in the "What was achieved?" section above, in particular getting two publications out and designing the next prototype, is to a very large extent due to Aiwu's hard work on the project. Without him, the EIC R&D effort at Florida Tech would very likely collapse. His design work on the common GEM foil is also directly benefitting two other groups in the eRD3/eRD6 consortia. Due to the low overhead rates at Florida Tech, his employment is a very cost-effective investment for the consortium. Consequently, we anticipate that we will request that funding be provided to renew his position for another year in FY17.

Stony Brook University:

The calculations and modifications for the evaporator refurbishment design have to be finalized. This is a non-trivial task since the evaporator has a significant volume which has to be evacuated, making the design choices for the refurbishment a well-thought through process.

University of Virginia:

- ✔ The production and tests of the new readout design on a smaller scale is a critical step before we can confidently go for the large size prototype. This is an area we would like to investigate in the next six months.

Yale University:

Hybrid Gain Structure for TPC readout
Critical issues remain the same: develop methods for operating a TPC at high data rates while maintaining low ion feedback, good energy resolution and robust operation (low discharge rate).

Additional information:

Anticipated future budget request for new EIC R&D funds.

Brookhaven National Lab:

We anticipate the following funding request for the next round of EIC R&D funding in FY17.

1. Support for beam test - **$15k**
2. Travel - **$3k**
3. Expendable materials and supplies **- $12k**
4. Design and materials for new chevron readout patterns - **$10k**
5. Parts and materials for investigation of GEM/Micromegas operation - **$10k**
6. New optics for VUV spectrometer - **$10k**

Total without overhead - $60k
Total with overhead - $90k

Florida Tech:

1. Salary for Aiwu (fully loaded) - **$95k**
2. Construction of next EIC FT prototype - **$14k**
3. Travel - **$7k**
4. Support for beam test - **$7k**

Total fully loaded - $123k

Stony Brook University:

1. Design and fabrication of snowflake readout patterns - **$12k**
2. Expendable materials and supplies **- $5k**
3. Support for beam test - **$10k**
4. Travel - **$5k**

Total without overhead - $32k
Total with overhead - $50k

University of Virginia:

1. Materials and Production of (U-V strips) readout board including the Zebra-Panasonic adapter boards - **$10k**
2. Design and materials and production of GEM support frames - **$4k**
3. Expendable materials and supplies **- $4k**
4. Travel - **$3k**
5. Support for beam test - **$10k**

Total without overhead - $31k
Total with overhead - $49k

Manpower

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located, what fraction of their time they spend on EIC R&D, and who supervised their work.

Brookhaven National Lab:
This work is being carried out by members of the BNL Physics Department as listed below. All personnel are paid by the BNL Physics Department.

Craig Woody, Senior Scientist (0.2 FTE)
Martin Purschke, Physicist (0.1 FTE)
Alexander Kiselev, Assistant Physicist (0.1 FTE)
Babak Azmoun, Physics Associate (1.0 FTE)
Bill Lenz, Technician (0.3 FTE).

Florida Tech:
Marcus Hohlmann, P.I., 0.25 FTE, not directly funded under this R&D program
Aiwu Zhang, post-doc, 1 FTE, fully funded under this R&D program, located at Florida Tech and supervised by M. Hohlmann.
Several undergraduates; unfunded.

Stony Brook University:
None of the labor at SBU is funded by EIC R&D. The workforce is listed below (in % FTE):

K. Dehmelt	Research Scientist	40%
T. K. Hemmick	Professor	10%
E. Michael	Undergraduate student	25%
N. Nguyen	Undergraduate student	25%

University of Virginia:
None of the labor at UVa is funded by EIC R&D. The workforce is listed below (in % FTE):

✔ N. Liyanage	Professor	25%
✔ K. Gnanvo	Research Scientist	40%
✔ V. Nelyubin	Senior Research Scientist	5%
✔ H. Nguyen	Post-doctoral	5%
✔ X. Bai	Graduate Student	5%
✔ R. Wang	Graduate Student	5%

Yale University:
None of the labor at Yale is funded by EIC R&D. The workforce is listed below.

R. Majka	Senior Research Scientist and Scholar	10%
N. Smirnov	Research Scientist and Scholar	50%
	Graduate Student	25%
	Undergraduate Student	25%

External Funding

Describe what external funding was obtained, if any. The report must clarify what has been accomplished with the EIC R&D funds and what came as a contribution from potential collaborators.

Brookhaven National Lab:

There is currently no other external funding for this R&D effort

Florida Tech:

Florida Tech has no external grants in nuclear physics. There is a base grant in HEP for CMS that has some synergy with R&D work on large-area GEMs.
All work described above was accomplished with the EIC R&D funds.

Stony Brook University:

There is no other external funding for this R&D effort.

University of Virginia:

- ✓ UVa has DOE basic research grant from Medium Energy Physics. The R&D work on Cr-GEM is funded with the research grant.
- ✓ The group also has DOE grants through JLab for the construction of the SBS GEM trackers.

Yale University:

None.

Publications

Please provide a list of publications coming out of the R&D effort.

Brookhaven National Lab:

1. "A Prototype Combination TPC Cherenkov Detector with GEM Readout for Tracking and Particle Identification and its Potential Use at an Electron Ion Collider", C. Woody et.al., Conference Proceedings of the 2015 Micropattern Gas Detector Conference, Trieste, Italy, October 12-15, 2015 (submitted).

2. "A Study of a Mini-drift GEM Tracking Detector", B. Azmoun et.al., submitted August, 2015 to the IEEE Transactions on Nuclear Science, currently under review.

3. "Study of a Short Drift GEM detector for future tracking applications at PHENIX", M. Purschke et.al., Conference Record Proceedings of the 2013 IEEE Nuclear Science Symposium and Medical Imaging Conference, Seoul, Korea, October 2013.

Florida Tech:

1. A. Zhang et al., "Performance of a Large-area GEM Detector Read Out with Wide Radial Zigzag Strips," Nucl. Instr. Meth. A811 (2016) 30-41, doi: 10.1016/j.nima.2015.11.157

2. A. Zhang et al., "R&D on GEM Detectors for Forward Tracking at a Future Electron-Ion Collider," 2015 IEEE Nuclear Science Symposium Conference Record, Nov 1-7, San Diego, CA.

Stony Brook University:

1. "Performance of a Quintuple-GEM Based RICH Detector Prototype", IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 6, DECEMBER 2015.
2. "Performance of a Quintuple-GEM Based RICH Detector Prototype", Nuclear Science Symposium Conference Record, 2015, IEEE

University of Virginia:

1. K. Gnanvo, et al. "Large Size GEM for Super Bigbite Spectrometer (SBS) Polarimeter for Hall A 12 GeV program at JLab", Nucl. Inst. and Meth. A782, 77-86 (2015). DOI: 10.1016/j.nima.2015.02.017

2. K. Gnanvo et al., "Performance in Test Beam of a Large-area and Light-weight GEM detector with 2D Stereo-Angle (U-V) Strip Readout", Nucl. Inst. and Meth. A808 (2016), pp. 83-92. DOI: 10.1016/j.nima.2015.11.071.

Yale University:

A publication is in preparation on the 2-GEM+MMG results described above and presentations were made at Quark Matter 2015 and IEEE/NSS/MIC 2015.

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[i] http://www-rnc.lbl.gov/~wieman/alice%20upgrade%20gating%20grid.pdf